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An Ecopath with Ecosim Analysis on Offshore Petroleum Platform Influences on Gulf of Mexico Red Snapper

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**AN ECOPATH WITH ECOSIM ANALYSIS ON OFFSHORE
PETROLEUM PLATFORM INFLUENCES ON GULF OF MEXICO RED
SNAPPER**

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science

in

The Department of Environmental Science

by
Valentin Gomez
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Abstract

Offshore oil and gas platforms have had a significant presence in the Gulf of Mexico since the 1950s. An important secondary function of these structures is that they provide artificial habitat to fisheries, most notably Red snapper. Policy changes intended to reduce the risk associated with aging infrastructure have reduced the number of standing platforms from 4044 to 1867 from 2001 to 2018. The effect this loss of habitat has on Red snapper was tested by creating three scenarios of platform changes and modeling the perturbation from 2005 to 2050. The simulation was accomplished using the ecological model Ecopath with Ecosim (EwE) where Ecosim executes the time dynamic portion of the model and Ecopath provides the initial mass balanced information for all species in the system. Fecundity estimates were used on a per platform basis and imposed on the egg production parameter of the Ecosim model to complete the scenarios. Results showed Red snapper fecundity on platforms to be relatively low resulting in minor changes in biomass for all three scenarios of offshore platform change. The most notable differences were in the types of vulnerability estimations used which dictates the interaction between organisms in the model. Based on these parameters offshore platforms were not seen to be a major contributor to Red snapper populations in any scenario or estimation method.

Introduction

According to 2018 data from the Bureau of Ocean Energy Management (BOEM), there are approximately 1800 petroleum platforms in the Gulf of Mexico [1]. Compared to its peak of about 4000 platforms 18 years ago, there have been considerable changes to the artificial reef habitat in the Gulf of Mexico. These vertical structures can serve as essential habitat for a variety of marine life and can result in lucrative hotspots for fishermen looking to fill their quota or limits. In Louisiana, over 70% of all recreational angling trips target oil and gas platforms in the Fishery conservation zone (more than 3 miles from shore) [2]. With this area being densely populated with platforms, there is large value in their presence.

The Gulf of Mexico is a productive body of water fueling the commercial fishing industry which is a large and important component of its total economic value. In 2014 commercial fisheries harvested about 544 thousand metric tons from the Gulf equating to just over \$1 billion [3], the largest revenue year since the beginning of the data set in 1950. However, the harvest size has declined since the 1980's when commercial fishing peaked at 1.2 million metric tons in 1984. Out of all Gulf coast states, Louisiana is the leading state in landing volume [4]. Commercial landing reached its max for Louisiana water also in 1984 at 862 thousand metric tons [5]. Over 72% of GoM catch is provide by Louisiana commercial fishing making it the largest contributor to the GoM U.S. fishing market (Figure 1.) [5].

Productivity in Louisiana can be attributed to many factors. It is apparent that Louisiana contains many platforms which adds to potential habitat for marine life as artificial reefs. Based on the production hypothesis of Bohnsack [6], the presence of artificial reefs could lead to the production of larger fish populations ultimately increasing the areas carrying capacity. If

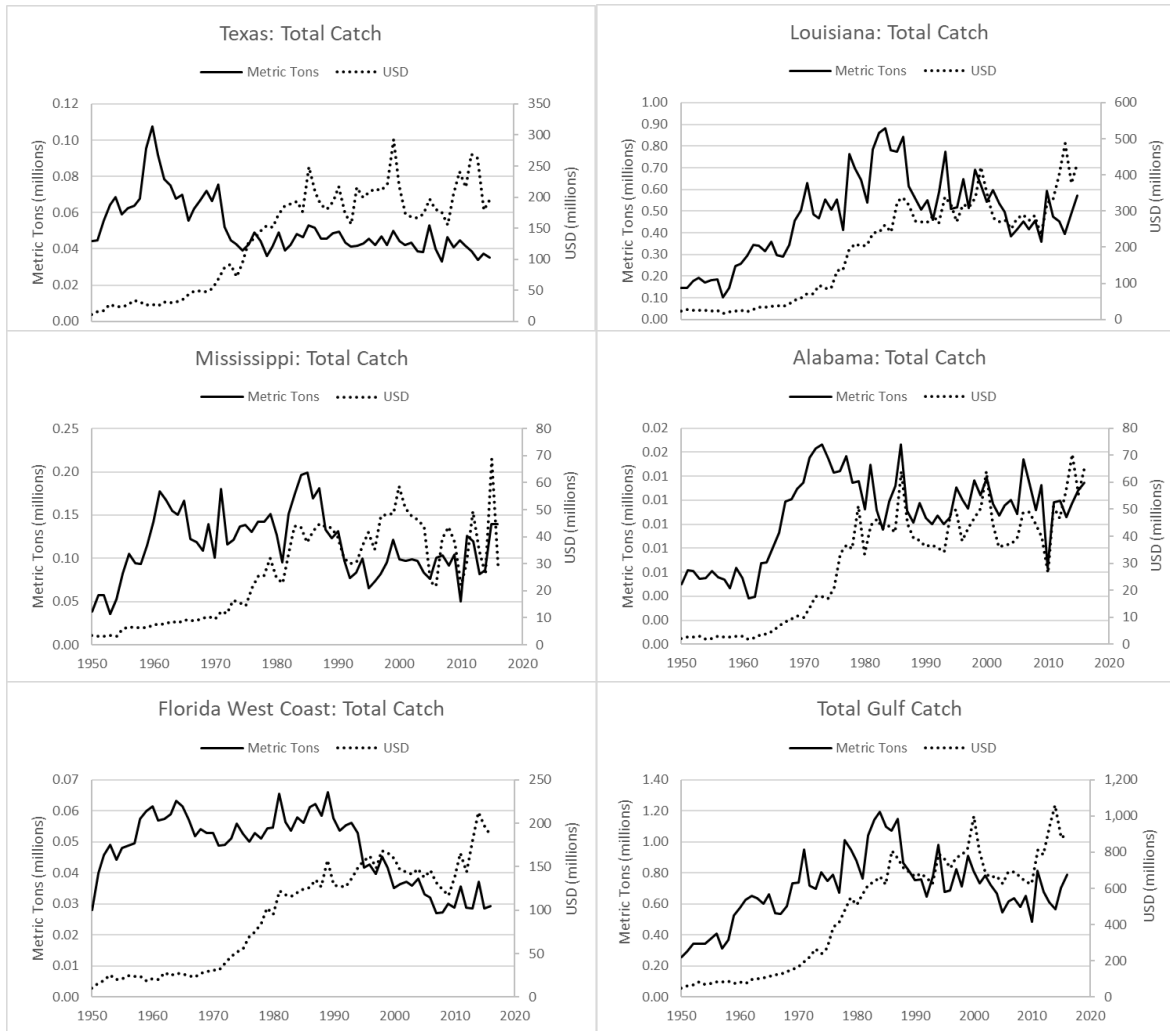


Figure 1. Total commercial catch in the Gulf of Mexico by state and total combined Gulf catch. Data from 1950 to 2016 in millions of metric tons and corresponding millions of USD value. Obtained from NOAA commercial landing data [5].

Bohnsack's production hypothesis is true, then fish being harvested from artificial reefs have the potential to replenish their populations with the additional resources those habitats provide. In turn this would help increase productivity in fishing markets that utilizes artificial reefs as a means to offset mortality. It has been seen in Japan that artificial reef programs have generally been seen to directly increase fishing effort and increase catch while indirectly decreasing working hours and operation cost [7].

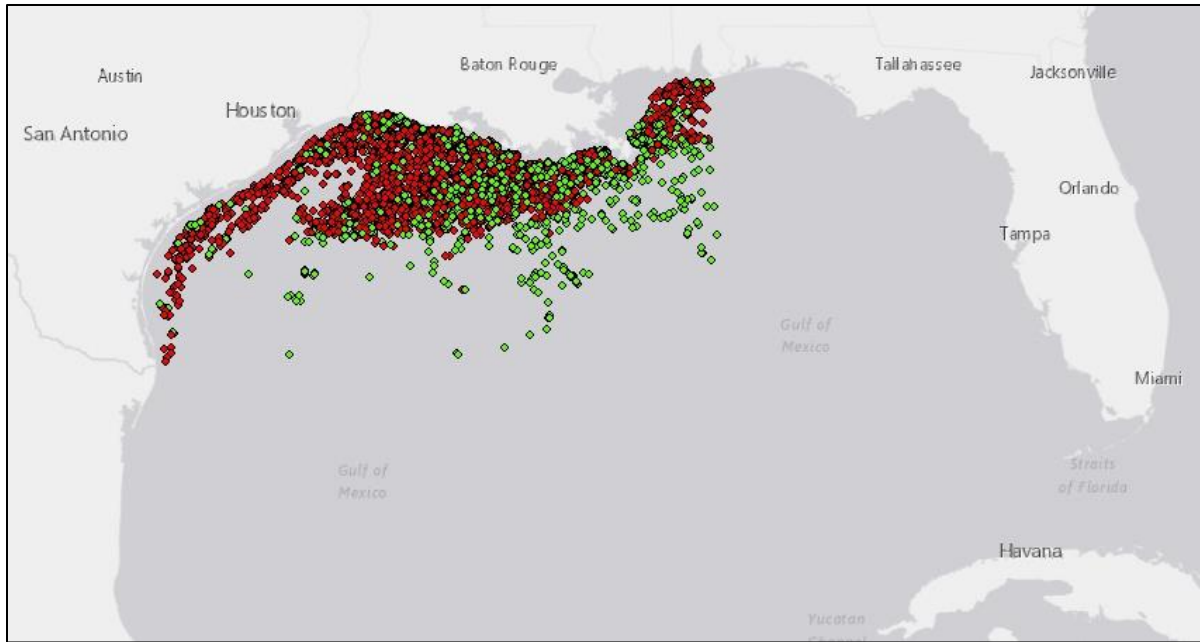


Figure 2. Map of platforms in the Gulf of Mexico as of 2019. Current standing platforms (green). Total removed platforms (red). Adapted from BOEM [1].

Alternatively, Bohnsack's attraction hypothesis may attribute the increase in fish population at artificial reefs to be due to the nature of marine life to aggregated towards structures rather than recruitment, growth of fish to reproductive age, happening at those locations [6]. This alternative hypothesis would imply that fish are not reproducing on artificial reefs and fecundity is below ideal. The attraction hypothesis would potentially result in populations of fish from other natural sources to relocate to artificial sites where they are not contributing to the spawning stock biomass, reproductive capacity, at their full potential. In the Mediterranean Sea, floating artificial structures have been used to culture mussel and oysters and in turn attract a variety of fish [8]. Although different from offshore platforms the concept remains the same. The availability of food at

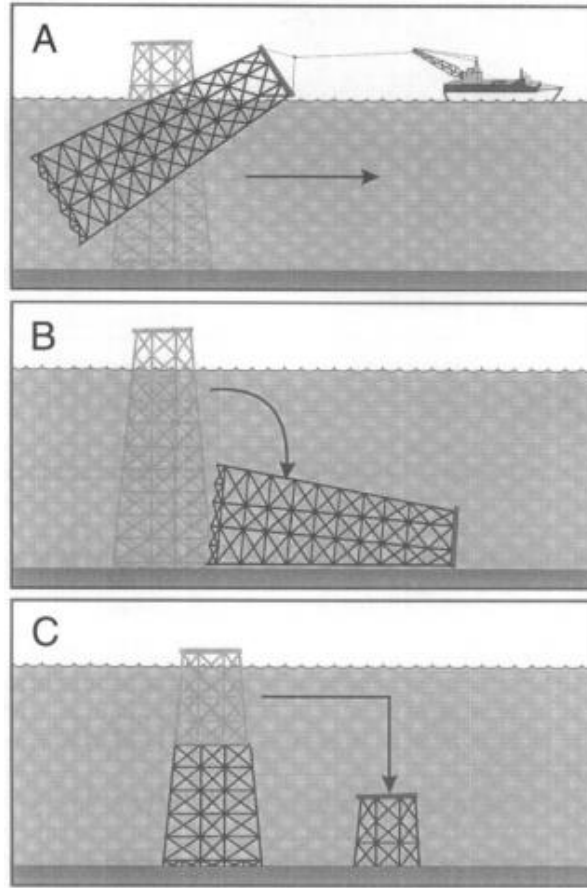


Figure 3. Decommissioning methods for taking down standing platforms to safe heights. (A) tow and place, (B) toppled in place, (C) Partial removal. (reproduced from Dauteville [10])

artificial reefs attracts fish which can then be harvested. In sum, offshore platforms may increase carrying capacity for some organism but can also be seen as a fish attractant making them an ideal location to harvest fish.

As of 2018 there have been a total of just over 5000 platforms removed from the GoM, platform comparisons are shown in Figure 2. Given that platforms comprise the largest network of artificial reefs in the world, this can be seen as a great loss of habitat [9]. However, the rigs-to-reef program activity seeks to add more artificial reefs using retired platforms. The rigs-to-reef program began with the signing of the National Fishing Enhancement Act into law (Public Law 98-623, Title II) in 1984 [10]. Since the creation of the Louisiana Artificial Reef Program (LARP), there

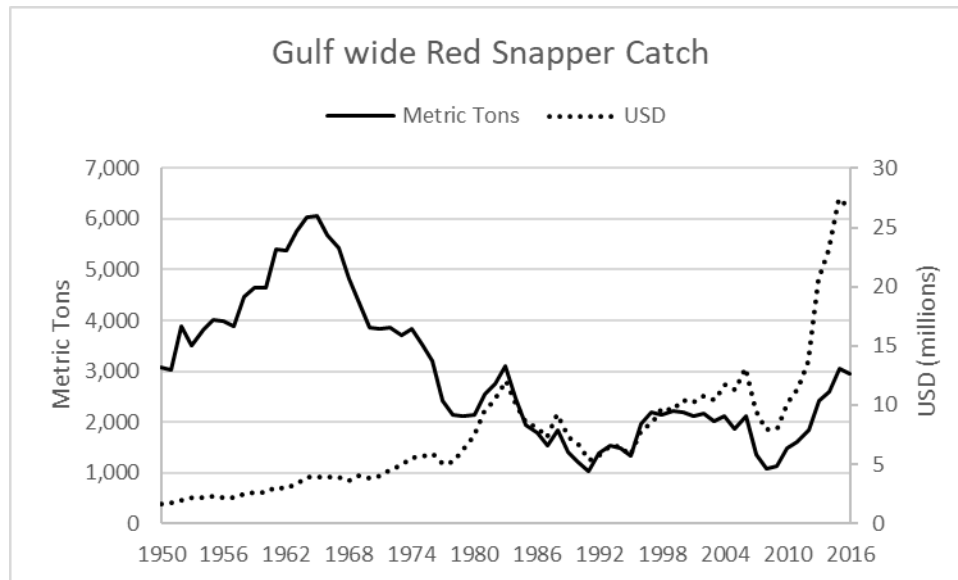


Figure 4. Total Gulf of Mexico Red Snapper commercial catch in metric tons from 1950 to 2016. Produced from NOAA commercial landing data [18].

have been 71 offshore reefs created using 320 obsolete platforms [11]. These platforms are either towed to site, toppled-in-place, or partially removed (Figure 3) [12]. The addition of these artificial reefs potentially contributes to the total available habitat in the GoM.

Studies using ROV surveys have found that standing platforms have greater species diversity compared to partial and toppled platforms [13]. Although there have been limited studies comparing different platform reef structure types, there is evidence that standing platforms contribute more vertical habitat leading to larger species diversity. Standing platforms may be more valuable in terms of sheer height of artificial reef structures. Furthermore, Stanley and Wilson [14] used hydroacoustic technology to survey three standing platforms and found well over 10,000 fish in each with one estimated to be over 25,000 fish. The extra height of complete platforms goes a long way in supporting fish populations which is to say that they are potentially more effective than other forms of artificial reefs. Although no biomass test was conducted alongside these hydroacoustic surveys, the sheer numbers provide a compelling argument for standing platform fish populations. The resulting loss in habitat from the decommissioning of

standing platforms may be offset by programs like rigs-to-reef but, there may still be some loss. The overall effect of the reduction in standing platforms on fisheries is what this paper will aim to discuss.

The species that will be used to assess platform influences will be Red snapper *Lutjanus campechanus* for their abundance and affinity for platforms [15] [16]. Shipps and Bortone [17] also noted that the presence of oil and gas platforms enhanced production of Red snapper and altered their distribution in the Gulf of Mexico. From 1880 to 1950 most catch was concentrated in the eastern Gulf but after the 1950s with the development of offshore platforms the distribution of Red snapper catch began to shift drastically to the western Gulf where most platforms were being installed [17] (Figure 2). Red snapper also hold high economic value in the gulf states with commercial catches reaching close to 3,000 metric tons in 2016 and bringing in a total of over 26 million USD (Figure 4) [18]. Red snapper has been managed since 1980s and has undergone routine stock assessment since then making them a widely studied species [19].

The feeding habits of Red snapper vary throughout their lifetime and size class. The size classes studied by Szedlmayer and Lee [20] in the GoM were from 18mm to 280mm and at size classes less than 60mm standard length (SL) Red snapper diets were found to consist of mainly shrimp, chaetognaths, squid, and copepods, whereas the larger class sizes of 60mm and above shifted to fish prey, greater amounts of squid, crabs, and continued consumption of shrimp (for size reference see Figure 5 [21]). This change in diet was indicative of the habitat shift they experienced from open habitat to reef habitat at around 70mm SL [20]. A similar study found that age 0 (27-100mm total length (TL)) Red snapper in the GoM consumed large amounts of shrimp, squid, and copepods [22]. After age 1 (180-276 mm TL) they began consuming more fish, crabs, and squid and by the age of 3 and above (>336 mm TL) they shifted to primarily fish and crabs [22]. This



Figure 5. Red snapper caught in the Gulf of Mexico. Picture taken from Sea Grant in the Gulf of Mexico website [21].

change in diet to more crabs in was also verified in a gut content analysis study by Kaylan et al. [23] where they collected data from juvenile, sub adult, and adult Red snapper finding that adult diet mainly consisted of crabs, 90%, with juvenile diet distributed more equally between crabs, fish, shrimp and gastropods [23].

Spawning for Red snapper occurs from April through September in nGoM in which after they are buoyant and hatch 2.2 mm TL and reach settlement at 16–19mm TL in about a month [24]. Settlement for juvenile Red snapper occurs on complex structures in which they are attracted to such as low-profile reefs or coarse shell material and can include production platforms and pipelines [25]. As they grow older (age 2+) they seek out larger structures like shallow artificial reefs such as offshore oil and gas platforms which provide shelter and feeding opportunities in both the upper and lower water column [24]. Older fisher (age 3+) will move to deeper natural reefs and the oldest of fish (age 8+) utilize deep open habitats since at that size they are typically invulnerable to most predation [24]. This shift in habitat can also be seen in a study by Dance and

Rooker [26] where they used fisheries independent data to model the relative distribution of Red snapper across the GoM shelf for juvenile, sub-adult and adult groups [26]. Juvenile Red snapper were found to be closer to the coast whereas sub-adults began shifting to deeper water, closer to the shelf, and finally adults were in largest abundance at the shelf and deeper waters [26].

Red snapper can live over 50 years and reach maturity by 290mm fork length (FL) (determined by 50% of individuals in population exhibited reproductive organ development) [16]. This 290mm FL can be reached as early as 2 years of age in which it was also shown by Woods et al. [27] that Red snapper do in fact become mature at age 2 [27]. At this age they have been seen to have a high site fidelity to offshore oil and gas platforms where they have the potential to contribute to the total spawning population [24].

There are several types of models capable of assessing the perturbation of platforms on the GoM. This paper will only be utilizing one, Ecopath with Ecosim (EwE). This modeling program is user friendly with clearly stated inputs and outputs that allows for the effective manipulation of the model in question. Additionally, there is a large database of existing models and studies using this program that can be accessed on the EwE website (ecopath.org). Another modeling software that was considered was the Atlantis ecosystem model. The flexibility and complexity of this modeling program to incorporate physical and biogeochemical system components through tropic levels could prove to be useful in developing large models [28]. However, to develop the model in this study in a reasonable amount of time it was concluded that EwE would be a better fit. The ease of use of the program and its range of parametrizations would allow for a more efficient modeling platform in this situation.

Ecopath with Ecosim has been previously used to assess fisheries in the Gulf of Mexico and on many other fisheries-based projects. Ecopath was initiated by Polovina [29] as a solution to model

the French Frigate Shoals, a coral reef ecosystem. Ecopath is mass balanced model comprised of groups (species) and their respective inputs to develop a web of interactions and predict basic estimates from that data. Currently Ecopath utilizes two master equations, one to describe the production term and the other is used for the energy balance of each group, which will be described later in the paper [30]. This portion of the modeling program accounts for only a fixed time period (usually one year). For a time-dynamic assessment of a study area the Ecosim portion of EwE can be used. Ecosim developed with the efforts of Walters et al. [31] by creating a set of differential equations from the original Ecopath procedures while incorporating appropriate functions to parametrize environmental characteristics such as vulnerability (flow control), consumption, and fleet dynamics. Through the use of EwE it is feasible to create the necessary conditions to model most perturbations in a system throughout several years.

Assessing fishery policy and management is a frequent use for EwE. EwE allows for the parameterization of a variety of policy options for implementation in wide array of areas. In the West Florida Shelf EwE was used to simulate management plans and fishing effort to predict changes in biomass throughout the trophic levels [32]. Here they were able to find that the management plan in question resulted in the decrease in several lower trophic level species [32]. Similarly, Martell et al. [33] and Wang et al. [34] tested different management policies for the optimum status of fishing activities and ecosystem health in the Strait of Georgia and the Pearl River Estuary (China Sea) respectively. Exploring fishery policies and management with EwE can be extremely useful for gaining important insight into systems of interest in an efficient manner.

Quantifying restoration efforts is an essential task for determining the success of projects. With EwE it has been possible to parametrize models in such a way to represent the changes that certain restoration project has on the environment. Frisk et al. [35] assessed the biomass gains from marsh

restoration in the Delaware Bay by adjusting biomass ratios in EwE simulations. In instances such as these a pre restoration model can be made and adjusted to assess the differences if restoration has not occurred compared a model where restoration did occur. Louisiana has also undergone several restoration projects some of which include diverting freshwater of the Mississippi River into wetlands to restore estuaries. The Caernarvon freshwater diversion was one such project that was modeled in EwE by de Mutsert et al. [36] to show the effect of changes in salinity had on nekton in the estuaries. These studies support EwE's capabilities to describe environmental changes and their flexibility in parameterizing different ecosystem perturbations.

There have been several Ecopath models created for the GoM, some that include an Ecosim study and some that do not. An extensive study by Vidal [37] created a large web of feeding interactions to described the fisheries impact and show the robustness of the GoM by using all portions of the EwE program, Ecopath, Ecosim, and Ecospace. Ecospace, which introduces spatially dynamic components into the model, will not be covered in this study but has been extensively reviewed in others such as in Walters et al. [38]. A more specific model of the coastal areas of the GoM was created by Walters et al. [39] using 63 biomass pool that encompass high trophic level species, such as sharks, to the lowest which included phytoplankton. This model however, did not include marine mammals. A more up to date model by Sagarese et al. [40] of the northern GoM included marine mammals and other groups for a total of 75 functional biomass groups. This model is most noteworthy for having the highest connectivity and system omnivory when compared to other GoM models [40].

There are limited studies relating to platform specific interactions and even fewer pertaining to model development with these structures. This study aims to develop a model that can potentially assist with future management of fisheries and more importantly test the resilience of Gulf of

Mexico fisheries to changes in artificial habitat created by standing platforms. The base of this project will begin with the Ecopath model developed by Sagarese et al. [40]. This model contains the most extensive amount of information available which will make for a solid foundation for the Ecosim portion of this study to function off of. The Ecosim portion will essentially build on the Ecopath model and provide insight to the effect removing platforms have on the Gulf of Mexico fisheries.

Background

Study Area

The Gulf of Mexico encompasses more than 1.5 million km² and borders the United States, Mexico, and Cuba. This large, semi-enclosed basin is connected to the Atlantic Ocean through the Straits of Florida and Yucatan channel. This system receives currents from the Yucatan channel and flows out through the Straits of Florida creating eddies and anticyclonic turns that make up the Gulf Loop Current [41]. The area modeled would be the northern section of the GoM which is comprised of approximately 310,000 km² covering 2,934 km of U.S. coast line from Brownsville, Tx, to the Florida Keys and extends out to about 400 m in depth (Fig. 6) [40].

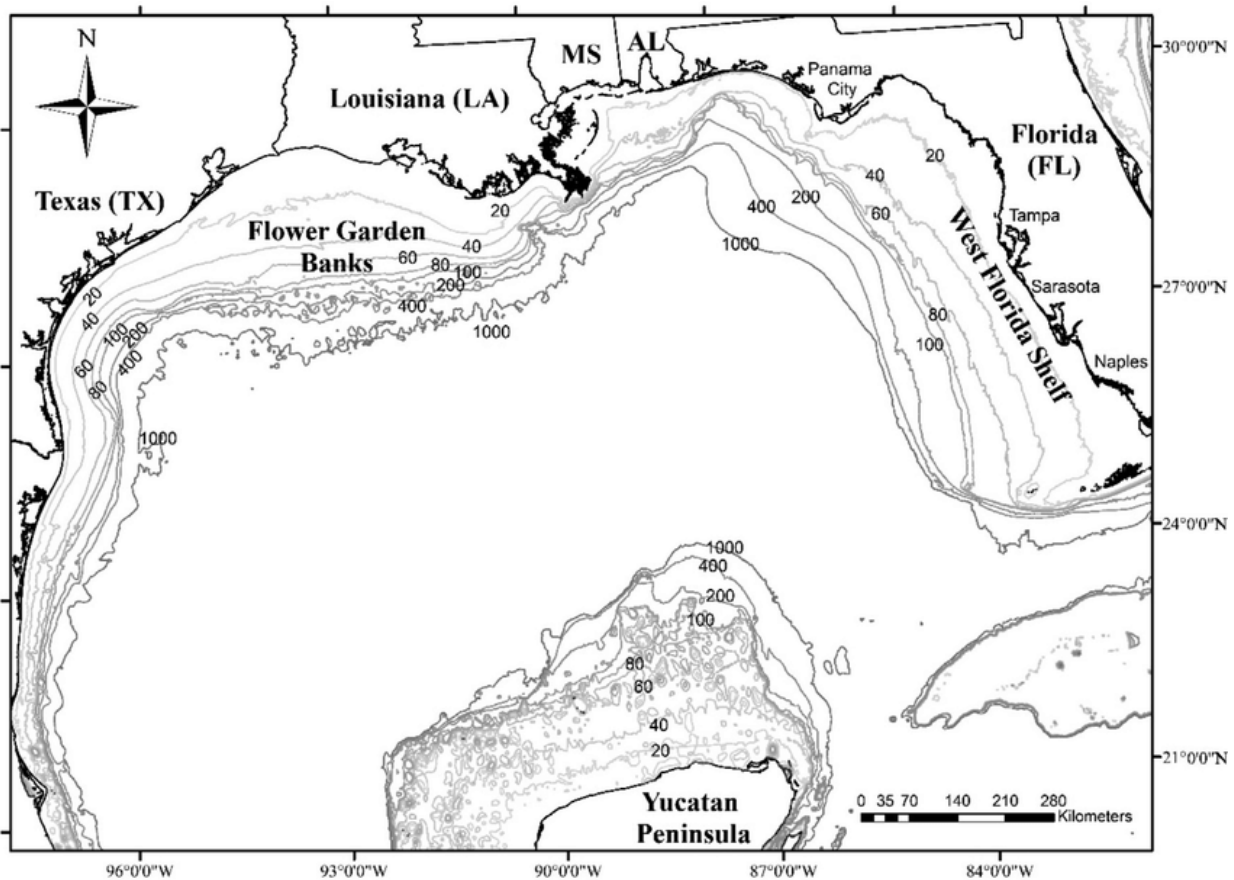


Figure 6. Map of the northern Gulf of Mexico with depth contours. The study area consists of 310,000 km² from the U.S. mainland to roughly along the 400 m depth line. Adapted from Sagarese et al. [40].

Ecopath

The mass-balance modeling approach of Ecopath is comprised of two master equations. One to describe the production term (P_i) (Eq. 1) and one for the energy balance for each group (Eq. 3) [42]. The components for the functional biomass groups i can be divided into the following:

$$P_i = Y_i + B_i \cdot M2_i + E_i + BA_i + P_i \cdot (1 - EE_i) \quad \text{Eq. 1}$$

where P_i is the total annual production rate of group i ; Y_i is equal to the total annual fishery catch rate of group i ; B_i is the biomass of group i in t/km²; $M2_i$ would be the instantaneous predation rate for group i ; E_i is the annual net migration rate of group i (emigration – immigration); BA_i is the annual biomass accumulation rate for i ; EE_i is other mortality for i . In a more simplistic form, it could also be defined as (Eq. 2) [30]:

$$\text{Production} = \text{catches} + \text{predation mortality} + \text{biomass accumulation} + \text{net migration} + \text{other mortality} \quad \text{Eq. 2}$$

After the conditions for the production term of each group are met and estimated the mass balance energy between groups energy can be ensured with (Eq. 3) [42]:

$$Q_i = P_i + R_i + U_i \quad \text{Eq. 3}$$

where Q_i is consumption for i ; R_i is the respiration term for group i ; and U_i is unassimilated food. Consumption for group i can also be defined as the total intake of biomass per year for that specific group; expressed as t/km²/year. A broken-down analysis of the consumption for group i of other functional groups is described in the diet composition sheet of Ecopath. Based on the premise that consumption is equivalent to the sum of somatic and gonadal growth, metabolic cost and waste products by Winberg [43], Ecopath rather focuses on estimating losses and does not explicitly include gonadal growth [42]. Respiration and unassimilated food are usually estimated in Ecopath but can be manipulated if enough information is present.

There are four inputs needed to satisfy the minimum requirements for the basic parameter information: B_i (biomass), P/B_i (production biomass ratio), Q/B_i (consumption biomass ratio), and EE (ecotrophic efficiency or other mortality). Of these four inputs only three are required and the fourth is to be estimated. It is recommended that B_i , Q/B_i and P/B_i are specified while leaving EE to be estimated within Ecopath [30]. Leaving EE to be estimated allows for the model creator to use that as a check for mass balance within the system. Values for EE varies between 0 and 1 with groups approaching 1 to be considered to be under high predation pressure [30]. Therefore, groups with EE over 1 would assume that parameters inputted do not agree with mass balance in the model operations and would need to be adjust for balance to be achieved. Mass balance of the model would then be achieved when all EE values fall below one [44].

Other parameters required for a complete Ecopath model includes the creation of a diet composition sheet and the definition of fishing fleets (if applicable). Parameterizing the diets of each group is probably be the most complex portion of the model, especially if diet studies of interested groups are limited. Each group's diet must sum up to 1. Cannibalism can be an issue when food for the same group exceeds 0.1 of that group, but this can be resolved with the addition of multi-stanza groups or juvenile and adult groups with their own respective diet compositions [30]. To define fishing fleets a matrix of landing and discards is required for every fleets/gear type. This portion is especially important when looking into changes in fishing mortalities.

The Ecopath model contains a total of 75 functional groups: one marine mammal group, one seabird group, one turtle group, eight shark groups, 53 fish groups, seven invertebrate groups, three primary producers, and one detritus group [40]. This Ecopath model was developed by Sagarese et al. [40] which allows for the development of this Ecosim model. All specifics of this base Ecopath model can be found in her journal.

Ecosim

Ecosim is the time-dynamic portion of EwE that allows for simulations of models throughout several decades. This time-dynamic simulation utilizes the information from the balanced Ecopath model to produce estimates of biomass and catch over time. Without the completion of a balanced Ecopath model the simulations in Ecosim would not be representative of what an actual system would do. In test models where EE was well over 1 (unbalanced model) biomass for test groups would either rapidly hit extinction or grow to unrealistic amounts. Ecosim expresses these estimates with a series of coupled differential equations derived from the Ecopath master equation (Eq. 1) and take the form:

$$dB_i/dt = g_i \sum_j Q_{ji} - \sum_j Q_{ij} + I_i - (M_i + F_i + e_i) B_i \quad \text{Eq. 4}$$

where dB_i/dt is the growth rate during the time interval dt for group i in terms of biomass, g_i is the net growth efficiency (production/consumption ratio), M_i is the non-predation or other natural mortality rate, F_i is the fishing mortality rate, e_i is the emigration rate, and I_i is the immigration rate [30].

There are several parameters in Ecosim for the group information to be adjusted if that is what is desired. For this study the Ecosim defaults were used with the exception of Feeding time adjusted rate. This function represent how fast organisms will adjust their feeding time to stabilize consumption rate per biomass [30]. All groups were set to zero except for the marine mammal group, the turtle group, and the sea bird group which were set 0.5, per convention of Ecosim developers [30]. Forcing functions can be hand sketched through the Ecosim interface and applied to appropriate groups. This parameter affects the Q/B ratio and can be applied to the search rate, vulnerability, arena area, or vulnerability and arena area. No forcing functions were applied to this

study but, the concept was initially explored and abandoned due to a lack of information on platform specific fish behavior.

The vulnerability feature of Ecosim is of great importance as it defines the flow control between predator and prey and allows for more accurate representations of food web interactions. Using the Ecosim default of 2 for all groups would assume that all species have the same effect on their prey despite changes in exploitation rates which would mean that all predators would be on the same point in their consumption curve [45]. In other words, a change in predator population for a given species would result in the same effect across all its prey population for every different predator. Vulnerability values based on trophic level have also been used in some studies. The differences in using default values as opposed to vulnerabilities set by trophic level is explored in a resilience test study which found that the severity of changes differed for both instances but ultimately stabilized within the same time frame [46]. The version of EwE used for this study had default values set to 0.3 and the trophic level vulnerability (TL) utilized a range of 0.3 to 0.8 [46]. The relative biomass values curve for TL was much steeper than the default vulnerability but it was clear that after the first years of the simulation both curves began to level out. Furthermore, Ecosim includes an ‘estimate vulnerabilities’ function that estimates vulnerabilities for each group, this function will be explored to a limited extent. There are several approaches to estimating vulnerabilities, but the most accurate method is inputting historic data into the ‘fit to time series’ function in EwE.

The Ecopath with Ecosim guide (November 2005 version) describes the importance of developing credible models that can reproduce historical results by using vulnerability searches [47]. Better estimates of vulnerabilities help to improve the model fit to historic data. Obtaining the best fit model is the goal of searching for vulnerabilities. The term vulnerabilities can be

defined as the rate at which the prey move from being vulnerable to not vulnerable when foraging [42]. Low vulnerability implies bottom-up control while high vulnerability implies top-down control. Christensen et al. [42] has found that EwE simulations have been especially sensitive to changes in vulnerabilities. Vulnerabilities can then be used to describe consumption (Q) using the following equation [42]:

$$Q_{ij} = \frac{a_{ij} \times v_{ij} \times B_i \times B_j \times T_i \times T_j \times S_{ij} \times M_{ij} / D_j}{v_{ij} + v_{ij} \times T_i \times M_{ij} + a_{ij} \times M_{ij} \times B_j \times S_{ij} \times T_j / D_j} \quad \text{Eq. 5}$$

where v_{ij} is the vulnerability rate of i for j , a_{ij} is the rate of effective search for i by j , B is the biomass for the respective group i and j , T_i represents prey relative feeding time, T_j the predator relative feeding time, S_{ij} the user-defined seasonal or long-term forcing effects, M_{ij} the mediation forcing effects, and D_j represents effects of handling time as a limit to consumption rate. From here the consumption rate is used in Ecosim for the time-dynamic simulation which consist of a series of coupled differential equation that when derived from the Ecopath master equation described in Eq.4. The interaction between Eq. 5 and Eq. 4 is the reason why there is a large emphasis on parameterizing vulnerabilities in Ecosim.

This study will present information based on three different vulnerability parameters: default setting, Ecosim estimated vulnerability, Stepwise Fitting Procedure. The Stepwise Fitting Procedure utilizes time series data to produce the best fit model based on the ideal vulnerability estimates for each group. Historically, time series fitting has been a manual process that utilizes the ‘fit to time series’ function in EwE but that process required individual searches which was a lengthy and tedious process [47] [48]. The stepwise fitting procedure that has now been implemented into EwE 6.5 automates the previous procedure making it more efficient and reduces the chances of human error [48]. This procedure has been utilized in Alexander et al. [49] and in Ahrens et al. [50].

The ‘fit to time series’ function utilizes a weighted sum of squared deviations (SS) of log biomasses from log predicted biomasses, scaled in the case of relative abundance data by the maximum likelihood estimate of the relative abundance scaling factor q in the equation $y = qB$ (y = relative abundance, B = absolute abundance) [47]. The imported time series data goes through this process to get a statistical measure of goodness to fit each time the simulation is run [47]. The function allows you to [47]:

1. Determine sensitivity of SS to the critical Ecosim vulnerability parameters (Vulnerabilities form), by changing each one slightly (1%) then rerunning the model to see how much SS is changed (i.e., how sensitive the time series predictions ‘supported’ by data are to the vulnerabilities).
2. Search for vulnerability estimates that give better ‘fits’ of Ecosim to the time series data (lower SS), with vulnerabilities ‘blocked’ by the user into sets that are expected to be similar, (i.e., user can search for just one best overall vulnerability, or for better estimates for up to 15 ‘blocks’ of predator-prey vulnerabilities).
3. Search for time series values of annual relative primary productivity that may represent historical productivity ‘regime shifts’ impacting biomasses throughout the ecosystem (for this search, the user must have linked a time forcing function to primary production using the Apply forcing function to primary production form and setting the i,i element of the forcing table for i = primary producers to the number of the forcing function).
4. Estimate a probability distribution for the null hypothesis that all of the deviations between model and predicted abundances are due to chance alone, i.e. under the hypothesis that there are no real productivity anomalies.

The stepwise fitting procedure automates these steps and outputs the scenarios from each proposed hypothesis.

Historical data in the form of time series data can be imported into EwE in several forms but must follow specific formatting guidelines to be uploaded successfully. The name, pool code, type of data, and years of the time series must all be present on the CSV sheet [47]. There are 11 types of data that can be used and they are as follows [47]: Force biomass (forcing), Relative biomass, Absolute biomass, Time forcing data (forcing), Effort data by gear type (forcing), Fishing mortality ((F) by pool (forcing)), Total mortality ((Z) by pool), Forced total mortality ((Z) (forcing)), Catches, Forced catches (forcing), Average weight (stanzas only). Each data type has its own use but for this study absolute biomass and catches will be used. This is similar to the methods used in Alexander et al. [49] for biomass time series data.

Methods

Model Design

A visual representation of the model dynamics are depicted in Figure 7 where it begins with an existing Ecopath model of the nGoM that encompasses the area of interest [40]. This base model is important for defining the initial characteristics of the Ecosim portion of the study. For all Ecosim models and Ecopath model must exist. From here the Ecosim portion is adapted to the necessary parameters to depict the change platforms have on the fishery represented by Red Snapper. To do this estimate of fecundity will be used together with platform change data. The three addition signs in Figure 7 indicate the three different scenarios of platform change that will be imposed on the fecundity information. Each scenario will then go through three different types vulnerability estimation. This is done to present all possible information and show the areas of uncertainty in model parametrization. The last step will be to run each simulation and acquire biomass outputs which will be assessed through difference graphs.

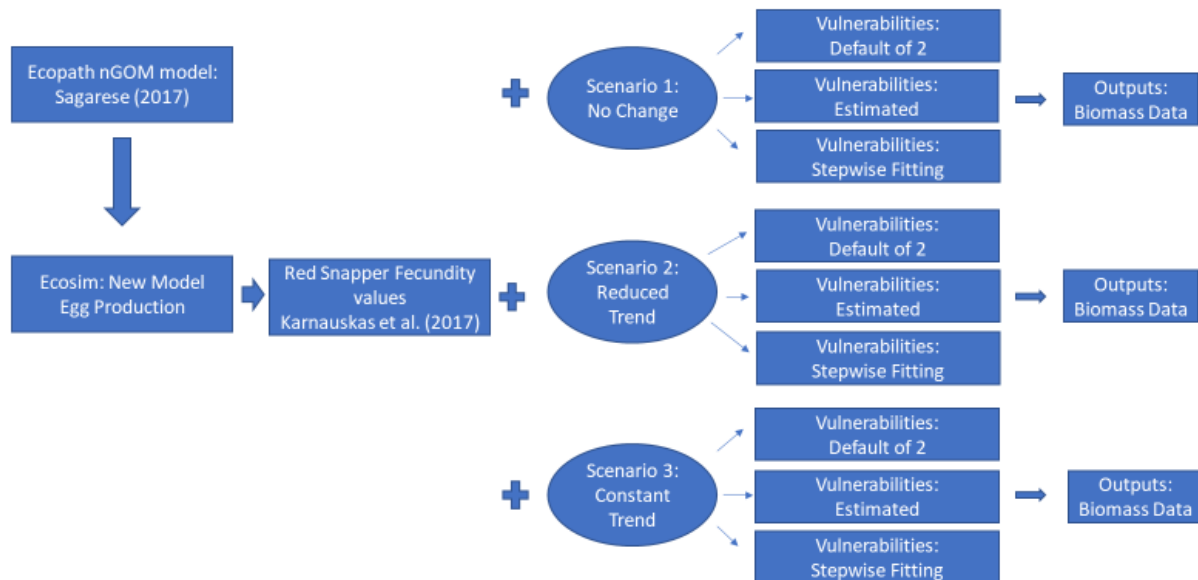


Figure 7. Conceptual design of Ecopath with Ecosim model. Biomass output process.

Group Information

There are 75 functional groups in the EwE base model from Sagarese et al. [40]. Ideally, it would be best to have time series information from all 75 groups, but so far in this study it has been narrowed down to 8 groups that affect the main organism of interest in this study (Red Snapper). In total there are 9 time series groups that will be used, including Red Snapper. The 8 groups were chosen based on the information from the diet matrix portion of the Ecopath model. This parameter defines the consumption percentages of each group for each prey. The groups with the largest percentage of consumption for the Red Snapper total consumption were chosen. These groups are as follows: (#4) Blacktip shark, (#6) Sandbar shark, (#9) Atlantic sharpnose Shark, (#17) Amberjack, (#18) Cobia, (#20) Adult King mackerel, (#29) Adult Red grouper, (#30) Age 0 Black grouper.

Data for all groups were collected from SEDAR Stock Assessments. Absolute biomass values were collected from Sandbar shark, Cobia, King Mackerel, Red Grouper, Black Grouper, and Red Snapper from their respective stock assessments [51] [52] [53] [54] [55] [19]. For Blacktip sharks, Atlantic sharpnose sharks, and Amberjack historic catches were used in absence of absolute biomass [56] [57] [58]. Data from 1990 to 2016 were collected however not all years of data were available for each group.

Vulnerabilities

Each scenario will go through three different vulnerabilities setting to compare the differences they have biomass. The Default setting was simply left at a vulnerability measurement of 2 with nothing more done. The Ecosim ‘estimate vulnerabilities’ function also allows the user to select what parameters they would like to use to estimate the vulnerability. In this instance, the vulnerabilities were estimated using the potential growth (set to a default of 2) and without

foraging time adjusted information. This setting compared to the others gave the lowest estimates. Other estimate options will not be explored in this study.

The Stepwise Fitting procedure utilized the absolute biomass information from the time series of Sandbar shark, Cobia, Adult King mackerel, Adult Red grouper, Age 0 Black grouper and Adult Red Snapper and historic catches for Blacktip sharks, Atlantic sharpnose sharks, and Amberjack. The number of vars estimated were 4 with spline point step size left at one. Baseline and Fishing iterations were run for a total of 10 iterations.

Egg Production

Egg production can be parameterized in Ecosim on a seasonal (monthly) or long-term (yearly) bases. This function will be used to identify the influence platforms have on fecundity in the GoM. Values for this parameter will be inserted in the simulation on an annual time frame but can also be seasonal (monthly) based. To manipulate this parameter the fecundity contribution of each platform will be imposed on two platforms scenarios. Scenario one being at a constant state or no change in the number of platforms from 2018 to 2050 (Figure 8). The second scenario is a continued state of change that follows the current trend of platform net change from 2005 to 2018 (Figure 9).

The contribution of each platform to total Red Snapper fecundity in the GoM will be needed in order to manipulate egg production. This is resolved by using existing data from Karnauskas et al. [59] where they developed estimates for Red Snapper from their spatial and statistical models to determine total contributions of each habitat type (artificial and natural, including platforms) by percent for number of fish, biomass, and fecundity. The fecundity estimate was used to determine the contribution of each platform by dividing the total percent contribution of platforms to fecundity by the number of platforms within the modeled area. In the Karnauskas et

al. [59] study they estimated total contribution of platforms to fecundity to be at 0.11% and noted that 2,014 platforms fell within their study domain. This results to each platform contributing about 0.00005% to total Red Snapper fecundity in the GoM.

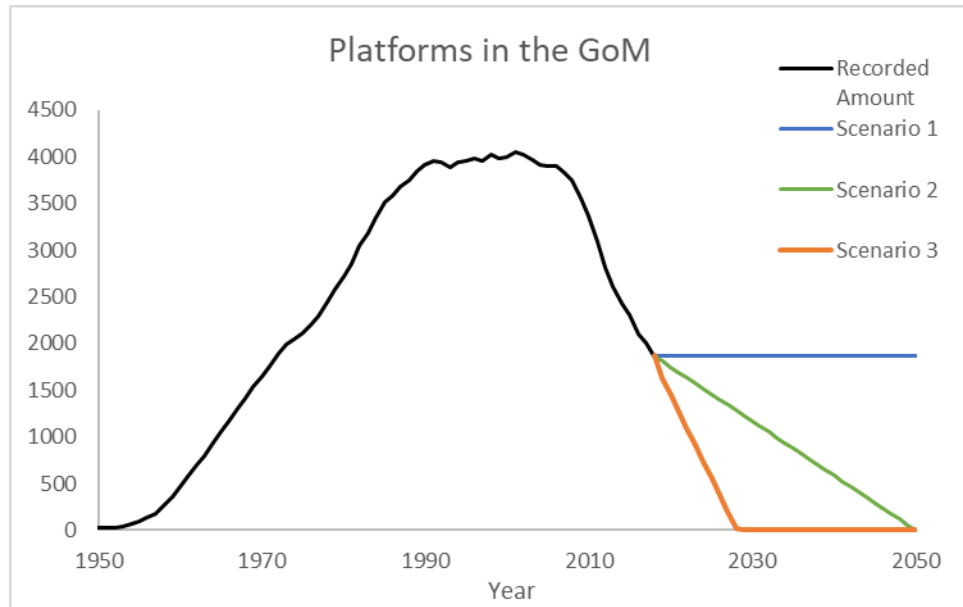


Figure 8. Standing Platforms in the Gulf of Mexico by year. Scenario 1 is the model run at 1867 standing platforms from 2018 to 2050. Scenario 2 is a reduction in the curve to remove all platforms by 2050 (end of simulation). Scenario 3 is the model run following the current trend equation. Recorded amount produced from BOEM platform structure data [1].

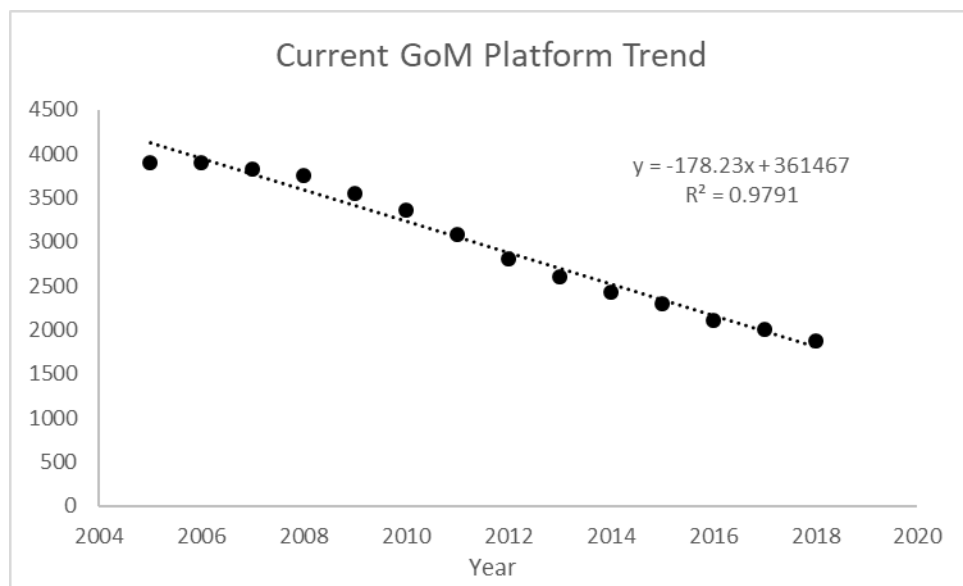


Figure 9. Gulf of Mexico platform trend used for scenario 3 model run. Simple linear line fit to recorded amount. Data from BOEM platform structure sheet [1].

Results

All three scenario results showed very little differences in relative biomass. This was as expected since Karnauskas et al. [59] estimates for total platform fecundity contribution were relatively low, 0.11%. As a direct result, egg production for 2018 platforms, which were the same for all scenarios, changed from full egg production of 1 in 2005 to a reduced egg production value of 0.999. Platforms for 2005 were reported to be 3894 while 2018 platforms in the nGoM were reduced to 1867 [1]. This is a 48% decrease in platforms over the course of 13 years. From 2018 and on platform values changed for scenario 2 and 3 and remained the same for scenario 1. This in turn caused differences in egg production values over the course of the simulation. However, the difference is fairly small with a max difference between egg production in scenarios 2 and 3 compared to scenario 1 to be 0.001 at the end of simulation, 2050.

Egg production for scenario 1 after 2018 remained at 0.999 until the completion of the Ecosim simulations. This is due to the model remaining at the same platform value of 1867. The three vulnerability settings used the same scenario 1 parameters. The only difference was the vulnerability values for each individual group. Default vulnerability (DV) setting results showed a max relative biomass value of 1.07 for all scenarios for the juvenile Red snapper. For the adult Red snapper, the max relative biomass values were just over 1.2 in all scenarios. In the Estimated vulnerabilities (EV) results the max values for the juvenile Red Snapper was about 1.09 in scenario 1, 2 and 3. The adult Red snapper EV results were both just over 1.32. The Stepwise vulnerability (SV) relative biomass results maxed out at slightly under 1.1 for juvenile Red snapper in all scenarios and also just under 1.3 for adult Red Snapper.

There was small difference between the scenarios that indicated that scenario 2 and 3 did in fact produced slightly lower relative biomass results than scenario 1. Scenario 3 produced the

lowest results which coincides with the reduced egg production levels. The largest difference that is easily seen in the relative biomass is that the DV setting produced results that were lower than both the EV and SV setting. This does show that the model is highly sensitive to vulnerability settings.

Vulnerability settings for the EV test estimated values for every single group. This was done through set functions in the Ecosim setting. It was observed that several groups contained values larger than 100 using this setting. Testing was done to assess the sensitivity of having large vulnerability values by setting a ceiling of 100. The results can be seen in Appendix Section 1. DV setting were simple and set all groups to a value of 2. The SV setting specialized the parameter based on the time series data for the groups mentioned previously. Most groups were still set to default values while the groups affecting Red snapper the most were set appropriately according to their time series data.

The time the model takes to stabilize is another feature that seems highly influenced by vulnerability setting. The beginning of each model rises significantly before leveling out in each vulnerability setting (Figure 10, 11 and 12). EV setting contained the highest degree of parameterization resulting in a high rise then fall of group biomass taking the longest time to stabilize. Oscillations in juvenile biomass are also present in the DV and SV but are more pronounced in DV simulations. DV setting had the lowest degree of parameterization which seemed to make the biomass results stabilize quicker but caused fluctuations in juvenile biomass. Although at slightly higher values SV settings stabilized at a similar rate to the DV setting but lacked the large oscillations that came with the lower degree of parameterizations.

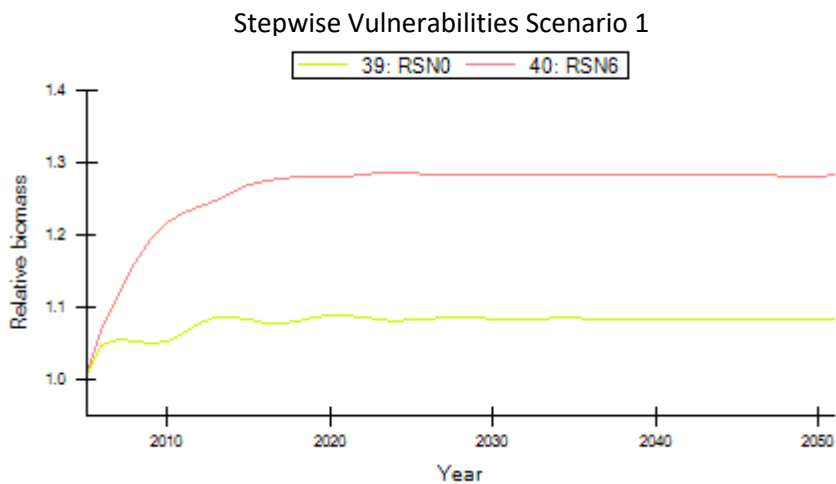
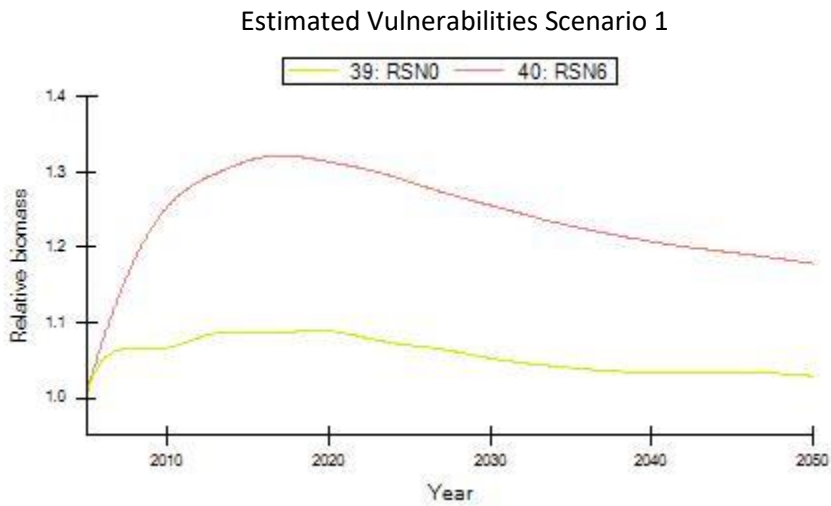
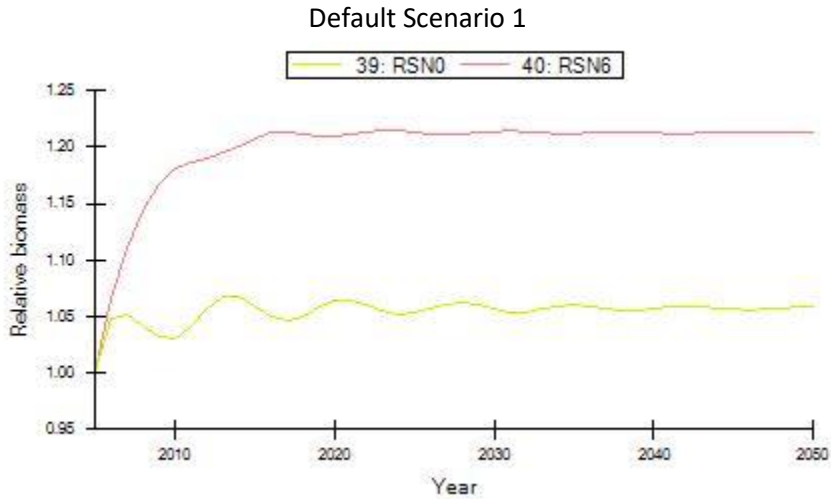


Figure 10. Model result of relative biomass from scenario 1 (no platform changes after 2018) starting year 2005 to 2050. Default results use vulnerability at 2 for all groups. Estimated vulnerability results use Ecosim Estimate Vulnerabilities function. Stepwise Fitting outputs utilize time series data for estimated vulnerabilities. RSN0 are Red snapper age 0 to 6. RSN6 are Red snapper age 6 and older.

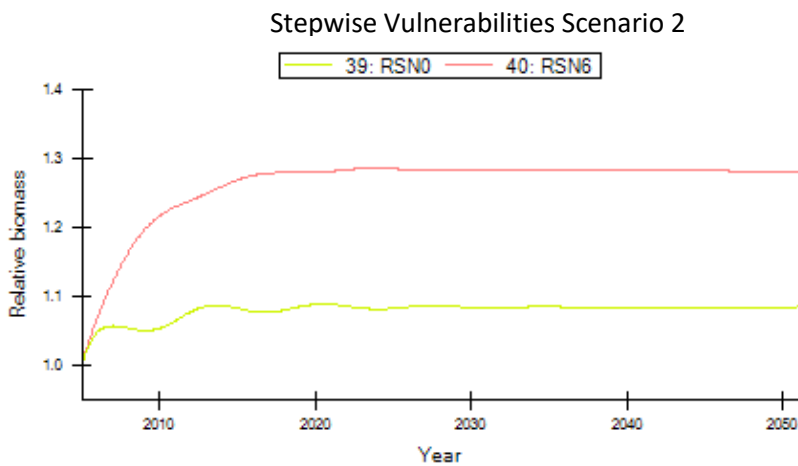
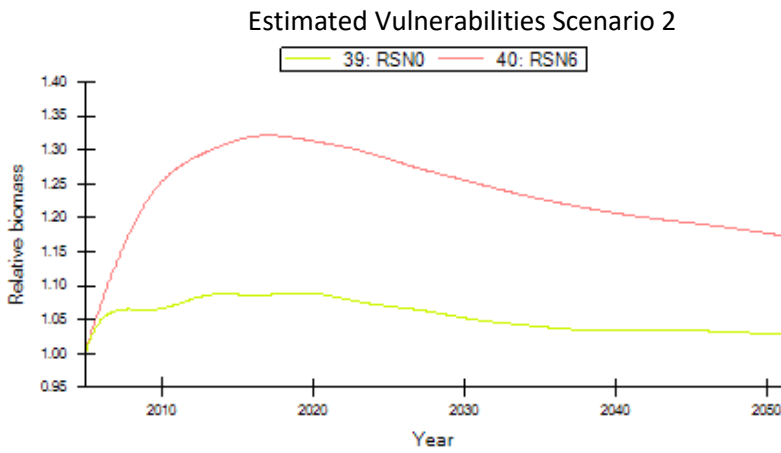
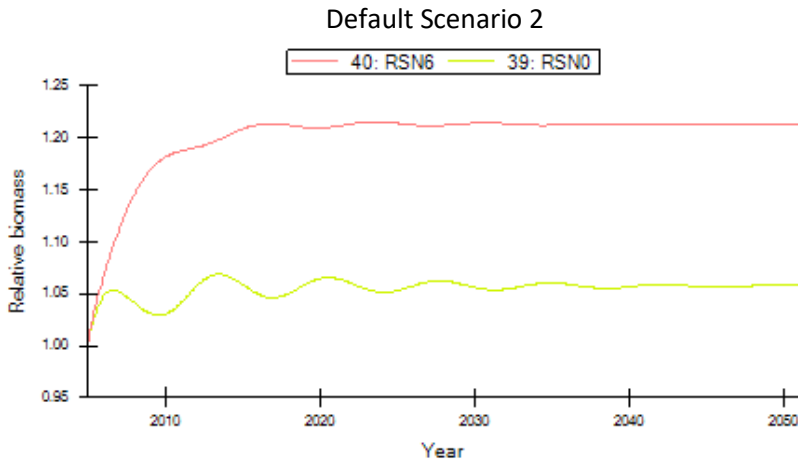


Figure 11. Model result of relative biomass from scenario 2 (reduced platform curve after 2018) starting year 2005 to 2050. Default results use vulnerability at 2 for all groups. Estimated vulnerability results use Ecosim Estimate Vulnerabilities function. Stepwise Fitting outputs utilize time series data for estimated vulnerabilities. RSN0 are Red snapper age 0 to 6. RSN6 are Red snapper age 6 and older.

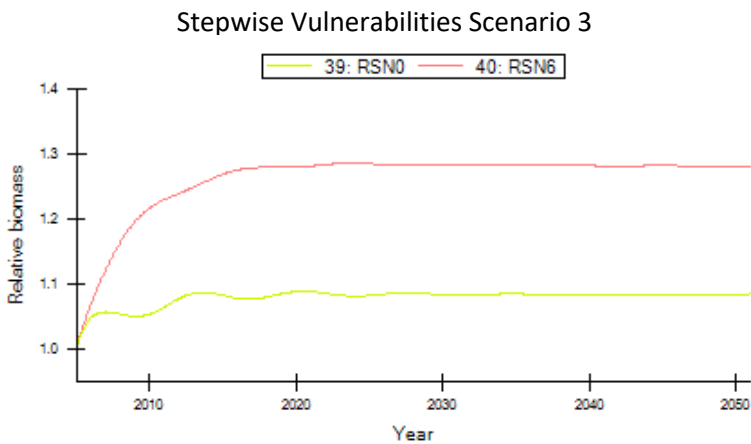
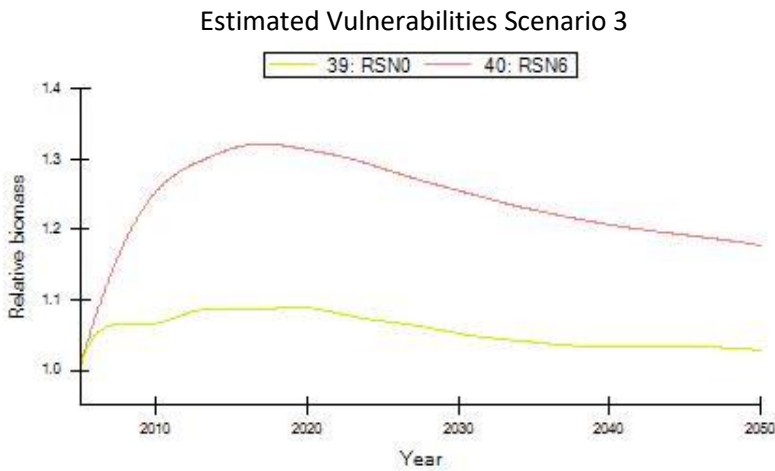
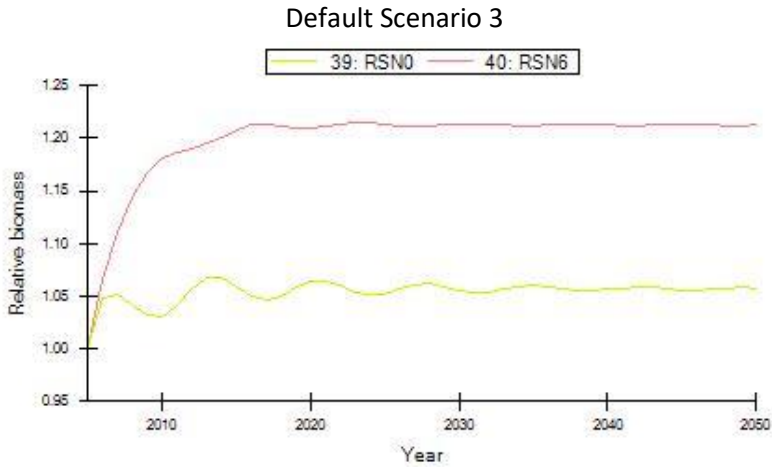


Figure 12. Model result of relative biomass from scenario 3 (continued platform trend after 2018) starting year 2005 to 2050. Default results use vulnerability at 2 for all groups. Estimated vulnerability results use Ecosim Estimate Vulnerabilities function. Stepwise Fitting outputs utilize time series data for estimated vulnerabilities. RSN0 are Red snapper age 0 to 6. RSN6 are Red snapper age 6 and older.

In order to assess the differences between the three scenarios and vulnerability settings the data was converted into purely biomass data and also converted from tons per square kilometer to kilograms per square kilometer. With this the differences became more apparent and allowed for a better analysis of the data. The juvenile and adult Red snapper biomass results were combined to give an absolute total Red snapper biomass estimate. A difference chart was produced from taking the difference of the combined biomass results of the Red snapper group of scenarios 1 compared to 2 and 3 (Figure 12 and 13). Overall, the biomass results for scenario 2 and 3 were lower than scenario 1 which indicates that the model is running as anticipated.

At the end of the simulation for scenario 1 vs 2, DV resulted in 0.0169 kg/km² of loss for a total of 5.20 metric tons of Red snapper biomass (Figure 13). When compared to scenario 1 total biomass at 2050 this results in a 0.02% decrease. EV showed the highest difference at 0.0378 kg/km² of loss, 11.67 metric tons of total loss for a 0.046% decrease in Red snapper. SV reported 0.0255 kg/km², a total loss of 7.87 metric tons for a 0.029% decrease (Table 1 and 2).

In scenario 1 vs 3 both the DV and SV settings reached a difference value of 0.0190 kg/km² and 0.0299 kg/km² at 2050, respectively (Figure 14). For the DV settings that results to a total loss of about 5.92 metric tons of Red snapper biomass in the nGoM accounting for a loss of 0.023%. The SV setting estimates there to be a total loss of 9.26 metric tons when compared to Scenario 1, a decrease of 0.034%. The EV was highest at a value of 0.0478 kg/km² or 14.81 metric tons of loss estimating to a 0.059% decrease (Table 1 and 2).

The biomass differences between scenarios 1 and 3 were lower for the DV settings compared to the EV settings by about 60% by the end of the simulation and 55% lower for the scenario 1 and 2 comparison. As for the Stepwise fitting function, it produced results roughly between the DV and EV in both comparisons. In scenario 1 vs 2 there was a much steadier increase than

compared to scenario 3 differences. This would be due to the constant removal of platforms until they are completely removed at the end of the simulation whereas scenario 3 is much faster decrease in platforms and shows 21 years of no platforms. Changes were still seen after the platforms were totally removed in 2029 in scenario 3 which indicates that any time lags can be seen during the rest of the simulation. EV produced higher differences with a steeper curve which could be attributed to the highly parameterized vulnerability setting which were set significantly higher than the DV and SV settings. SV settings did produce differences that fell between the DV and EV setting with a similar progressing curve as the DV. The difference between vulnerability settings showed that they are in fact important in determining the best fit model. However, in this case the differences are relatively small only being apparent when blown up to larger proportions.

Table 1. Total Red snapper biomass percent loss at end of simulation, 2050.
Values were calculated using scenario 1 total biomass.

Scenario	Default Vul.	Estimated Vul.	Stepwise Vul.
1 v 2	0.020	0.047	0.029
1 v 3	0.023	0.059	0.034

Table 2. Total Red snapper biomass in metric tons at end of simulation, 2050.

Scenario	Default Vul.	Estimated Vul.	Stepwise Vul.
1	25,947	25,159	27,417
2	25,942	25,147	27,409
3	25,941	25,144	27,407

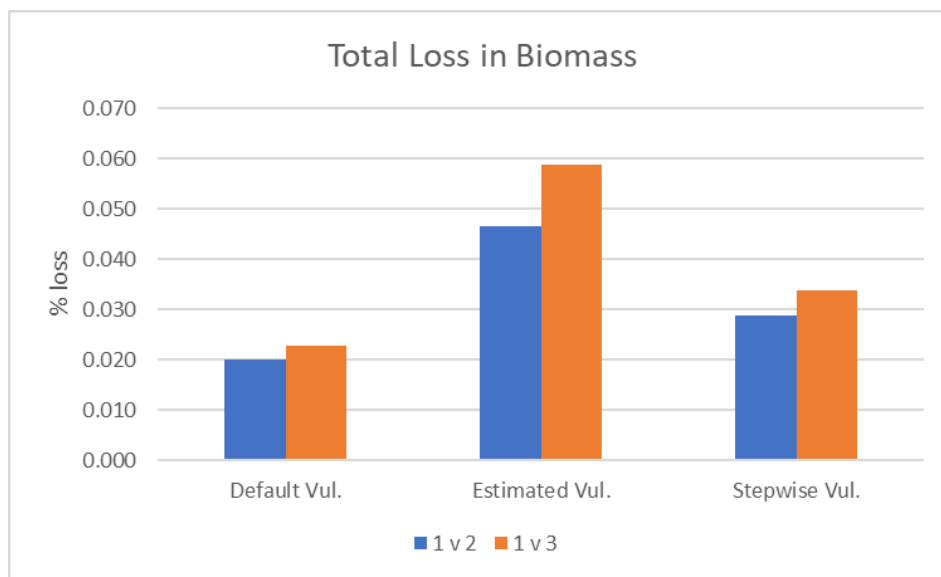


Figure 13. Juvenile and adult Red Snapper combined biomass percent loss when comparing to scenario 1 biomass at end. All three vulnerability settings shown.

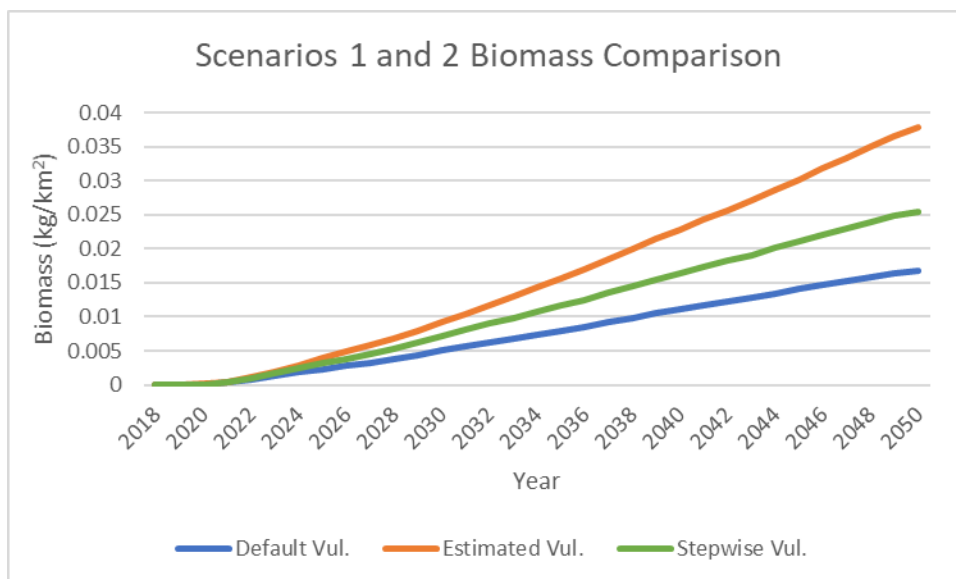


Figure 14. Juvenile and adult Red Snapper combined biomass scenario differences. Scenario 1 vs scenario 2. All three vulnerability settings shown.

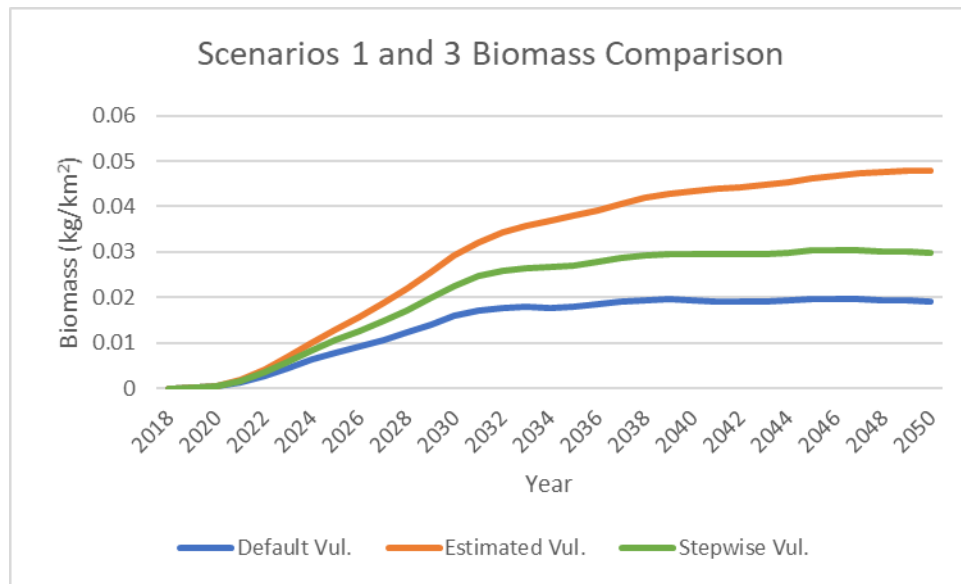


Figure 15. Juvenile and adult Red Snapper combined biomass scenario differences. Scenario 1 vs scenario 3. All three vulnerability settings shown.

Discussion

This study investigated the influences that offshore petroleum platforms had on fisheries that utilize these structures, more specifically Red Snapper whom have a strong affinity for platforms [16]. This was done using the EwE program which allows for a detailed layout of the food web interactions and utilizes the Ecosim simulation function to predict what perturbations in platform amounts would do to Red Snapper biomass values in the Gulf of Mexico. Along with this assessment is an analysis of the Ecosim vulnerability, or prey-predator flow control, settings which were manipulated to give other possibilities in the model. This is done to account for uncertainties in how varying prey-predator interactions affect this system.

All else being equal, if offshore platforms remained unchanged (scenario 1), we would see at the most a 0.059% increase in Red snapper biomass if following EV parameters for scenario 3. This is at the farthest extreme of the simulations tested where catch would theoretically be the lowest since there would be less available Red snapper to be caught. However, that 0.059% of the population would be spread out over the entire nGoM and could also consist of a portion that is uncatchable. This could be fish that are either in a difficult location to reach, not susceptible to fleet harvesting techniques, or are below harvestable size. These proportion are further extrapolated if we compare scenario 1 to the more probable scenario 2 where platforms are gradually removed until 2050 and with SV settings which use historical time series data. In this instance there would be 0.029% difference in biomass where less catch might be seen in scenario 2. Between scenario 2 and 3 the scenario with the least catch would be in scenario 3 where platforms are removed far faster, but this change might not be felt since it is a small portion of biomass being loss and a portion of that could represent a population inaccessible to fishing fleets.

All results indicate that changes in the platform amounts result in relatively low effects in Red snapper biomass, less than 0.06% in all tests. This was assessed using estimated fecundity values from Karnauskas et al. [59] on a per platform percent contribution basis and applied to the egg production parameter in Ecosim. This is one of several parameters available for use in the Ecosim program, but it was one that seemed most appropriate to use and where information was available to make accurate assumptions of the populations. Although low values were indicated, there were questions as to how responsive the program was to changes in egg production. To test the sensitivity of the egg production parameter an increase of 100-fold was implemented on the per platform fecundity values. This resulted in a fecundity increase from 0.11 to 11 percent for platform fecundity estimates. The results were as expected with an increase in biomass values proportional to the 100-fold increase. Each curve depicted the same patterns as the original egg production values with differences only being steeper slopes and higher values for the increased estimates. Overall, the program does respond to higher levels of fecundity which supports the program is performing as it should.

There is relatively high confidence in the fecundity values provided and in the Ecosim simulation estimates for platform contribution to Red snapper population. Karnauskas et al. [59] breaks down the distribution of Red snapper biomass in the nGoM as 13.3% present in artificial reef and of that 13.3% only 2.3% are utilizing platforms as habitat. It was also calculated that the largest percentage of Red snapper utilizing platforms as habitat were from the age class of 1 to 2 years of age [59], which is also supported by Stanley et al. [15], Render et al. [16], and Gallaway et al. [24]. By the age of 2 Red snapper are known to become mature, but while they may have entered the spawning population their batch fecundity (number of viable eggs released in a spawning) are at the lowest point of their life with age 6-35 females spawning about 50% more

than even 3 to 5 age females [60]. The low population proportion utilizing platforms as habitat (2.3%, [59]) combined with a high frequency of age 1 to 2 year individuals which of those mature have the lowest batch fecundity at age consequently, supports the findings that indicate population at platforms do not contribute a great deal to fecundity in the nGoM.

Fishing mortality could also be used to assess platform influence on Red snapper. However, it would be somewhat difficult to assess fishing mortality accurately because fishing fleets are aggregated together in the model to represent one whole mortality value. Fishing fleets can be defined and broken up into categories and there are longline, handline and shrimp trawl fleets defined in the Ecopath model that are used in parameterizing portions of the total Red Snapper fishing mortality [40]. However, there is not a habitat specified fishing fleet for platforms. If there was there would still be the issue of an aggregated fishing mortality value for Red Snapper.

Additionally, fishing effort can be manipulated which would allow for potentially adjusting the pressure put on the fishery by fleets that specifically target platforms for meeting their fishing quota or limits. As stated before, the Ecopath modeled fleets lack habitat specific fishing fleets. This limits the use of the fishing effort but is not a possibility that should be entirely set aside. Walters et al. [61] has used and seen benefits from utilizing fishing effort to parameterize their models and also describes the success of simulating fishing effort for fishes of Tampa bay and other Florida study areas. Fishing effort was manipulated to see how sensitive the fishery was to changes in the fishery. However, it was not used for reasons stated above. For information on these results see Appendix Section 2.

The results from the biomass comparison chart (Figure 12 and 13) proved to be helpful for assessing the smaller changes in biomasses between the three scenarios. The difference may not be very large and significant but if applied to areas where Red Snapper biomass is dense and

located near clusters of platforms could imply significant changes in Red Snapper fishery availability. Most platforms seem to be located along Louisiana shores and it could be inferred that if any region were to be impacted the most by a total loss of platforms it would be Louisiana offshore areas. However, this does not account for the adaptability of fishermen to adjust to changing circumstances. Fishermen could adapt fairly quickly to these changes and still acquire catches that compete with current amounts. This is an important underlying uncertainty to keep in mind.

Red snapper may not be the only fish of importance on platforms as there are other that are in relatively high abundance. Atlantic spadefish, Blue runner, and Bluefish can also be found on platforms in high abundance [14] [15] [62]. The loss of platforms may have potentially adverse effect on the population of these fish depending on how they utilize these structures. Reef associated fish, such as the Atlantic spadefish, could be greatly affected as they would utilize resource from the platforms the most [63] and have a high index of reef exclusivity (IRE) of 0.95 for platforms [62]. IRE was developed to describe the amount of species production that can be attributed to resources produced on the reef where a max value of 1 would indicate that the species is exclusively procuring resources from its reef [64]. For reference, Red snapper has an IRE of 0.05 which would indicate that it does not directly use platform produced resources but may find some benefits in the form of protection [62]. A low IRE found in Red snapper on platforms specific habitats may not be the same if Red snapper were on other natural habitats. In this case the IRE value is compared to resources that are used by the species from nearby natural habitats and platforms may only be a source of refuge from predation. Red snapper that inhabit platforms may have foraging grounds outside of that area which in turn results in a low IRE despite it being a reef fish. Alternatively, Bluefish and Blue runner are pelagic fish and therefore have a low IRE (0.01

and 0.10, respectively) [62]. This would indicate that these fish are not utilizing resources produced by platforms, but they may feed on fish that surround the platform and therefore an absence of platforms may affect their resource availability. Additional resources and experimentation would be necessary in determining the full extent of platform removal on other species.

As mentioned previously, platforms are not necessarily entirely removed leaving no structures behind. As described, they can be toppled in place, towed to another location or partially removed to meet nautical navigation standards [12]. Visually from the surface they may appear to not be present but may in fact still be providing some vertical substrate below the surface for Red snapper to aggregate or reproduce at [6]. This might introduce another type of uncertainty in habitat availability but in this study only standing platforms are assessed to report full productive potential. The estimates for fecundity also only represent standing platforms. There is no mixing of toppled or repurposed platform in the estimate of fecundity obtained from Karnauskas et al. [59]. Instead, platforms that have been decommissioned and repurposed as artificial reef sites are represented in another category separate from platforms but still within artificial structures. The issue with this is that this category deemed as simply ‘reefs’ does not differentiate between repurposed platforms and other structures. The value associated with this estimate, 6.24% (uncertainties up to 13.68%) for fecundity, would include all artificial reefs excluding standing platforms [59]. Additionally, the estimates for the reef values contain large uncertainties due to discrepancies in the true number of artificial reefs. If a value for fecundity could be obtained for artificial reefs created from decommissioned platforms, then it could be incorporated into the study for a further evaluation of the influences of offshore petroleum platforms on the Red snapper fishery.

The loss of platforms has varying effects on the population of Red snapper as well as for the ecosystem service of the structures used as fishing destinations. Red snapper populations might

see slight decreases in egg production as a direct result of losing standing platforms and therefore decrease populations amounts by a very slight margin. Another direct result of losing standing platforms is the loss that might be seen by fishermen both recreational and commercial alike. Since these structures are easily visible and relatively closer to shore than the nGoM shelf, they make for quick and easy fishing targets. The cost associated with fishing expeditions vary with fuel pricing and equipment but overall longer trips in search of different sites would increase expenses and decrease total profit or benefits from taking these trips. Without platforms fishermen may have to travel farther distance to reach productive locations. This would result in higher cost for both recreational and commercial fishermen. Alternatively, this could mean less fishing pressure for fish that would be located on platforms. From this viewpoint it could be inferred that a loss of platforms may result in some benefits to fish in the form of reduced fishing pressure. However, whether the loss and benefits offset each other is uncertain and further studies would be necessary to accurately estimate the true effects of a reduction in platforms especially when taking into consideration the adaptability of the corresponding ecosystem services.

Results in this study show that standing platforms are not directly contributing to the spawning population of Red snapper in large amounts, but there may be other lingering factors not captured by the EwE assessment. An example of this would be assessing the numbers of individuals surviving to older ages due to the protection from platforms. Escapement from platforms to other habitats could influence the productivity of the later generations of Red snapper. This could potentially lead to the increase of older Red snapper that are more fecund and contribute a greater amount to spawning population. Karnauskas et al. [59] estimates there to be 0.44% of Red snapper biomass present on standing platforms which supports the rationality that standing platforms are not a large source of egg production, however it was also estimated that the numbers of Red

snapper present is 2.31% which if whom are able to further mature and migrate away may contribute more to the total population. Coupled with over 2,000 decommissioned platforms that may be utilized as artificial reefs; the influences that all offshore platforms, both decommissioned and standing, may be largely understated.

Conclusion

Overall, this study shows the potential changes that varying platforms scenarios may have on Red snapper fisheries. It is not intended to be a stock assessment model but is instead meant to be used to improve methods in future stock assessments or management criteria development. The main goal of this project was to show the possibilities and capabilities of using Ecopath with Ecosim to develop an interconnected species model to describe platform changes and their effects on important fisheries in the Gulf of Mexico. This is one of many tools in our disposal that can be integrated into management decision and assessments. The most notable portion of this study would be that it utilizes an entire food web of interactions to display results of abiotic perturbation effects on one species throughout a large system.

The change in Red snapper even at the most extreme platform simulation was relatively low. The economic value of this loss when put in USD at the 2016 price of Red snapper (4.10 USD/lb., calculated from total lbs. harvested and the corresponding monetary value recorded by NOAA [18]) amounts to 133,881 USD. This value does not represent the total loss that would be seen in the Red snapper market but instead indicates the value or dollar amount in potential loss for the Red snapper population in the entire nGoM. To better put this into perspective the total economic value for red snapper in 2016 would be 683,344,015 USD (calculated from the SEDAR 2018 Stock assessment for Red snapper) [19]. The loss from a total removal of platforms is low and in a more real world setting with slower removal of platforms and adaptability of fish it would be even lower. With the current information and imposed parameters, the economic value of Red snapper is not greatly influenced by the loss of offshore petroleum platforms.

Appendix A. Vulnerabilities Test

Testing the sensitivity of high vulnerability values was done by imposing a max value of 100 to the Estimated vulnerability settings and comparing the results. This new setting was deemed Adjusted vulnerabilities (AV). The AV were tested with scenarios 1, 2, and 3 and the results were displayed in a similar manner to Figures 13 and 14 where the biomass comparison were shown on one graph for all settings. Additionally, to see the difference that results from imposing a ceiling to the EV the difference in total biomass for the nGoM was calculated.

The difference between the EV and AV settings were very small and were not apparent in Figures 15 and 16 with heavy over lapping occurring. With the calculated difference for the comparison of EV to AV it can be seen that there are some minor changes. In Figures 17 and 18 changes in biomass going from EV to AV remain in the hundreds for the entire nGoM. For the majority of the years AV is producing lower results at an average of $-23.248(\pm 48.852)$ kg for Scenario 1 vs 2 and $-44.707(\pm 83.325)$ kg for Scenario 1 vs 3. These values are distributed across the entire nGoM making them an extremely small percentage of change. For the 310,000 km² that it occupies it averages $0.00009(\pm 0.0001)$ kg/km² if scenario 2 is used and $0.0001(\pm 0.0003)$ kg/km² if scenario 3 is used. This would support the conclusion that given the parameters used vulnerability values larger than 100 have no significant effect on biomass changes for this model.

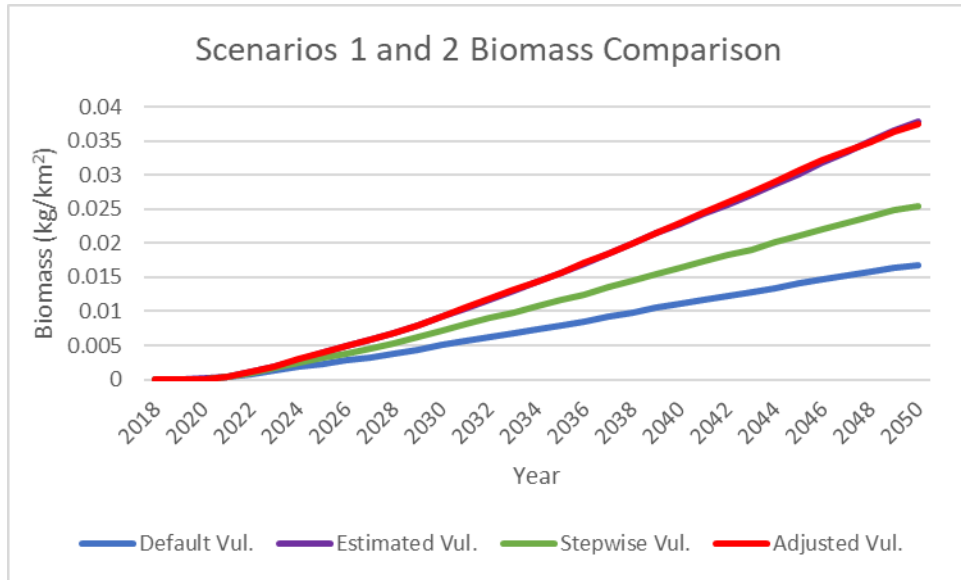


Figure A.1. Juvenile and adult Red Snapper combined biomass scenario differences. Scenario 1 vs scenario 2. All four vulnerability settings shown. AV overlaps the EV curve.

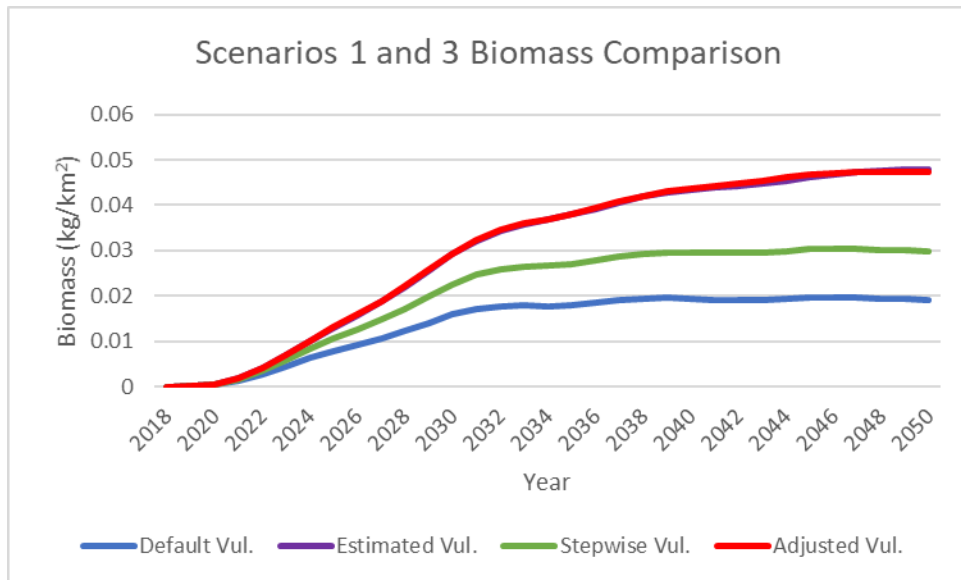


Figure A.2. Juvenile and adult Red Snapper combined biomass scenario differences. Scenario 1 vs scenario 3. All four vulnerability settings shown. AV overlaps the EV curve.

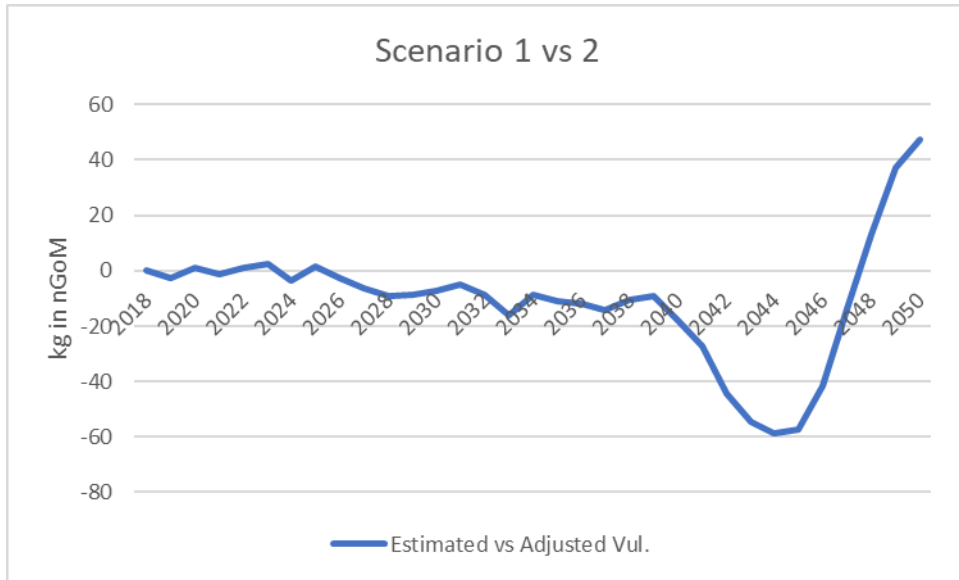


Figure A.3. Scenario 1 vs 2. EV compared to AV total change in kilograms for the nGoM.

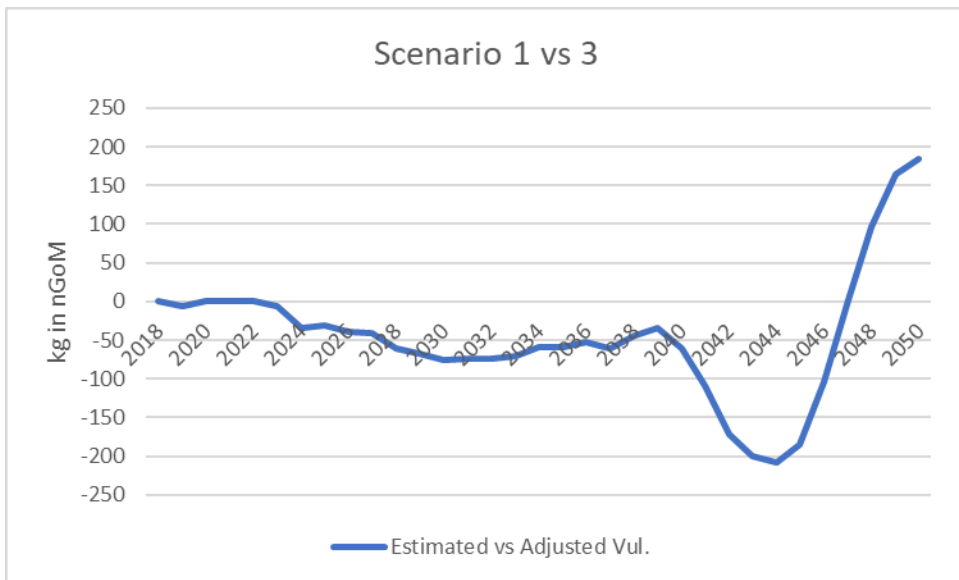


Figure A.4. Scenario 1 vs 3. EV compared to AV total change in kilograms for the nGoM.

Appendix B. Fishing Effort Sensitivity

Fishing effort was increased at 1% per year for the duration of the simulations. Fishing effort was also shut off completely to test both extremes. This was done to test the sensitivity of the Red snapper fishery to fishing. To isolate changes in only fishing effort egg production was not manipulated in these simulations. All other parameters were kept equal.

The relative biomass test all showed the same large increases in the first few years of the simulation (Figure 19 and 20). Larger increases were expected with fishing off (Figure 20) and flatter curves could be seen in a gradual increase in fishing (Figure 19). Juvenile fisheries did not seem to change as much as adult fisheries did. Some reduction was seen and the oscillation in population were still apparent. The adult fishery underwent major changes with high rises then extreme drops in population that correlate with the increase in fishing (Figure 19). The most interesting finding was that due to the increase in fishing there was a point where the Adult Red snapper population fell below the juvenile population. This would indicate a fishery that is unsustainable. On the other hand, adult Red snapper more than doubled when fishing was turned off and began to reach a high equilibrium (Figure 20).

Fishing effort is a major driver for biomass in EwE and Red snapper in this simulation are extremely sensitive. Manipulating this parameter would need to be done cautiously as it could have large effects in biomass. It would be most effective at determining the effects of policy changes which is not a factor being modeled in this study.

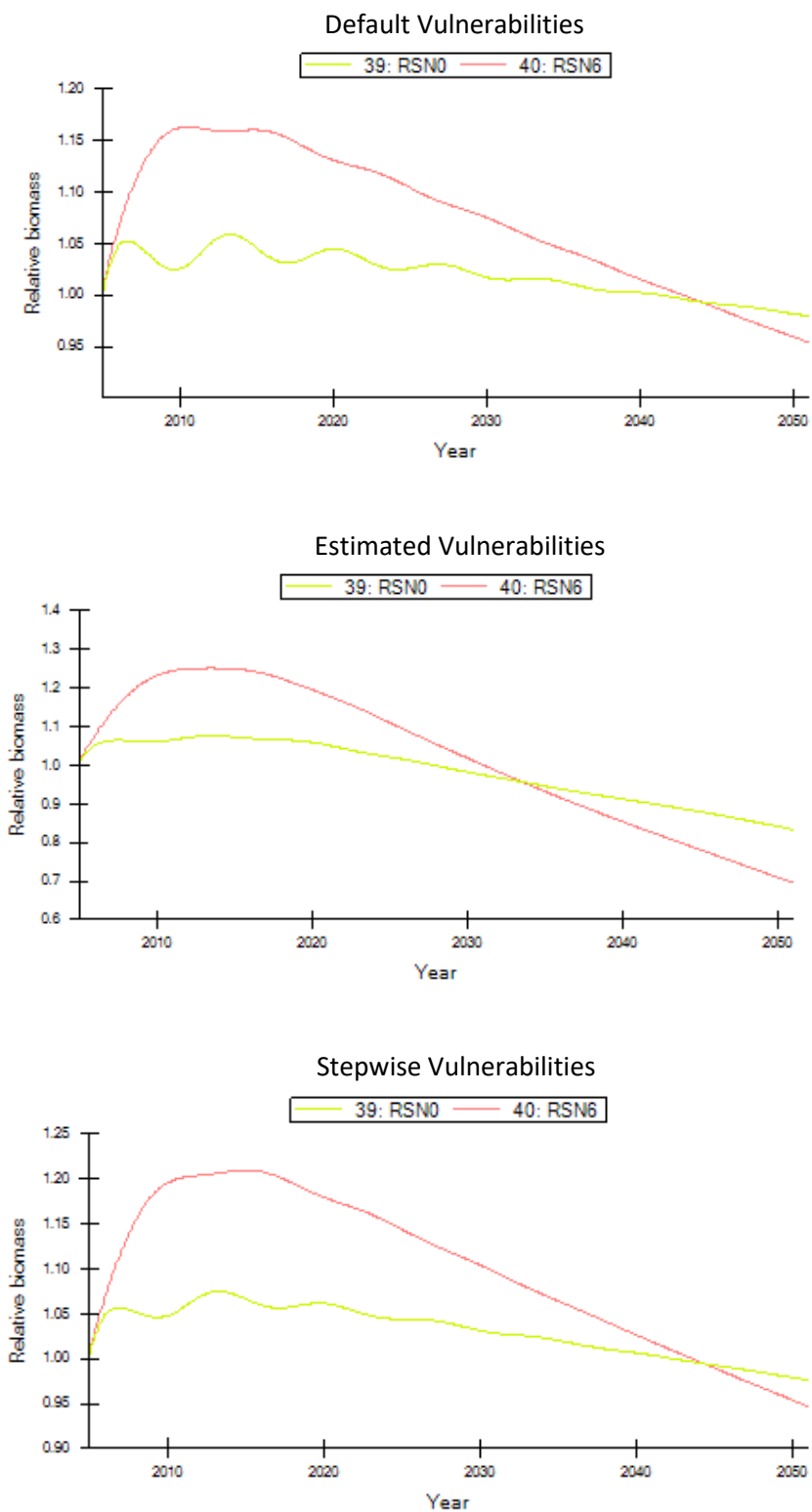


Figure B.1. Relative biomass results of fishing effort increased at 1% per year tested on all vulnerability estimation methods. RSN0 are Red snapper age 0 to 6. RSN6 are Red snapper age 6 and older.

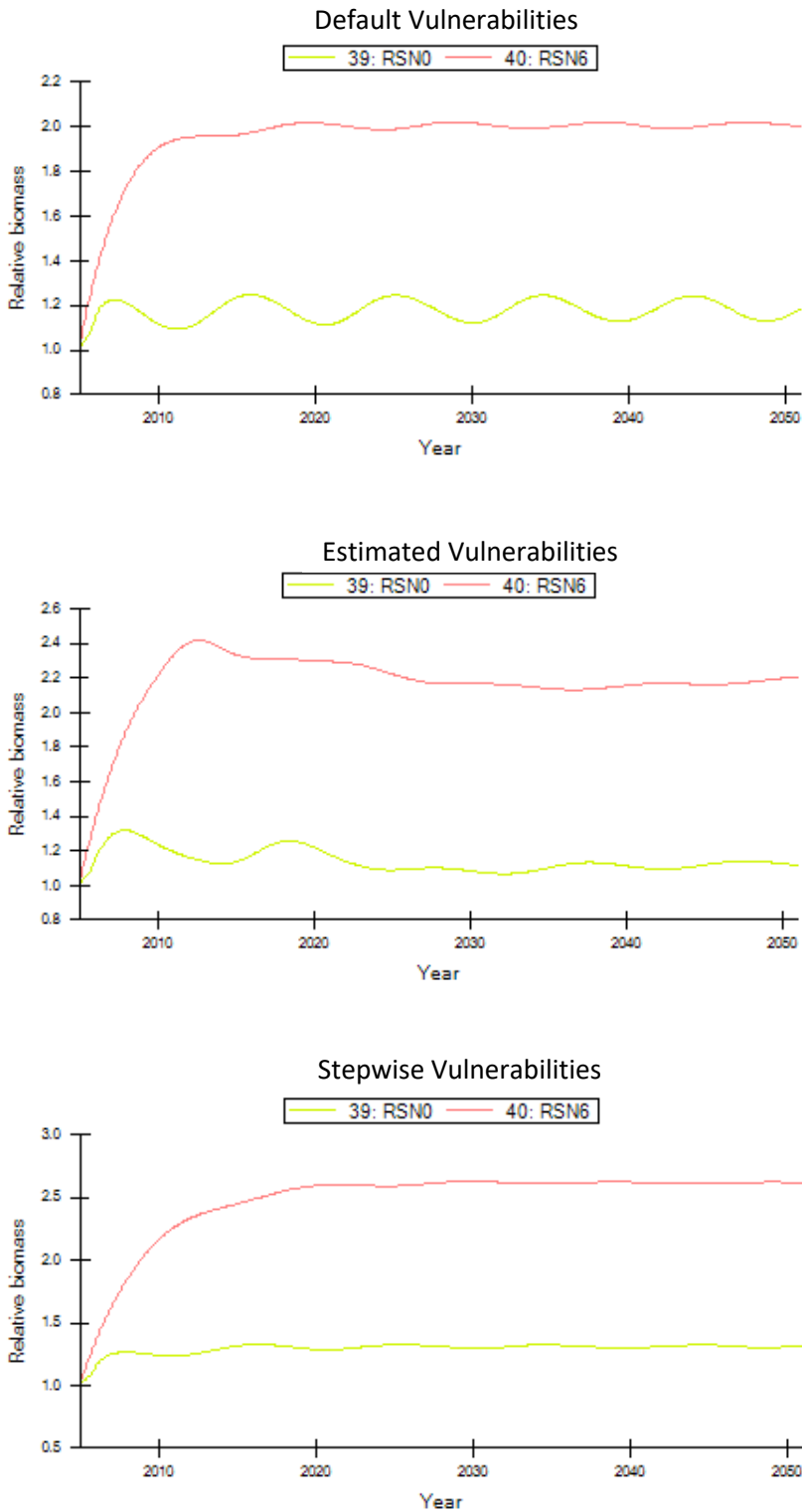


Figure B.2. Relative biomass results of fishing effort at zero on all vulnerability estimation methods. RSN0 are Red snapper age 0 to 6. RSN6 are Red snapper age 6 and older.

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Vita

Valentin Gomez, born in Texas, worked as a lab assistant in College Station as he pursued his Bachelor's degree from Texas A&M University. Upon receiving his degree, his interest in environmental health and quality led him to continue his academic career the following semester at Louisiana State University in the Department of Environment Science. After the completion of his Master's degree, Valentin will begin advancing his professional career in his home state of Texas. He anticipates receiving his Master's degree in May of 2020.